Theory of Bubbles in the ISM

Jane Arthur

Centro de Radioastronomía y Astrofísica
Universidad Nacional Autónoma de México
Campus Morelia

Local Bubble and Beyond II, Philadelphia: April 2008

Classical Theory

- Evolution in uniform media
- HII regions
- Stellar wind bubbles
- Supernova remnants

Classical Theory

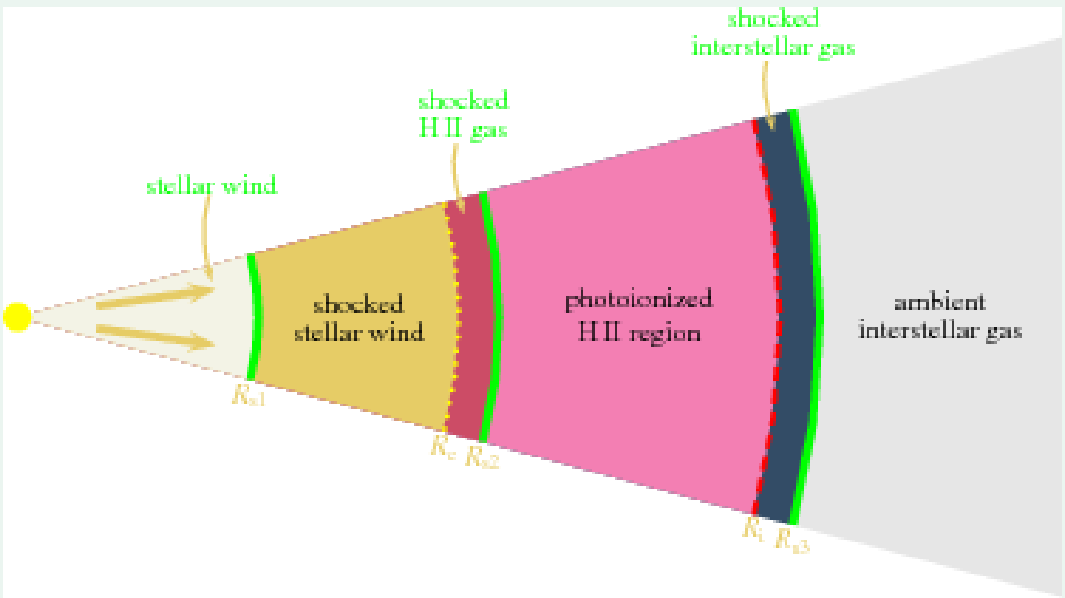
HII Regions

- Parameters: n_0, S_*, c_{II}
- Expansion rate: $R_i \propto t^{4/7}$
- Gas temperature constant: $T \sim 10^4$ K
- Ionized gas density uniform

Classical Theory

Stellar wind bubbles

- Parameters: n_0, L_w
- Expansion rate: $R \propto (L_w/n_0)^{1/5} t^{3/5}$
- Two-shock pattern
- Hot bubble of shocked stellar wind $T \propto V_w^2$
- “Cold” thin shell of swept-up ISM



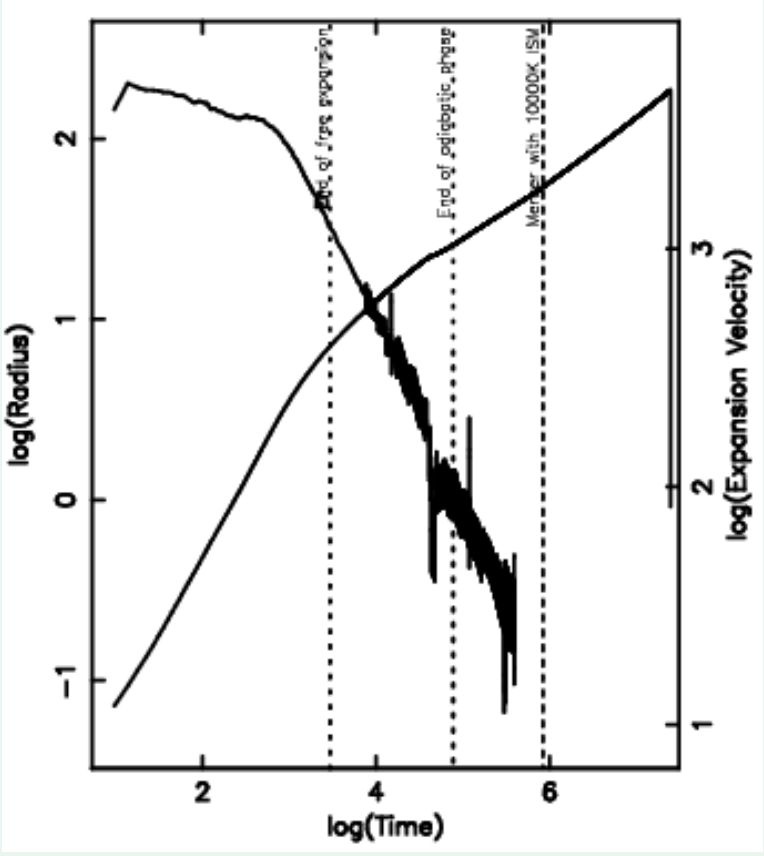
Classical Theory

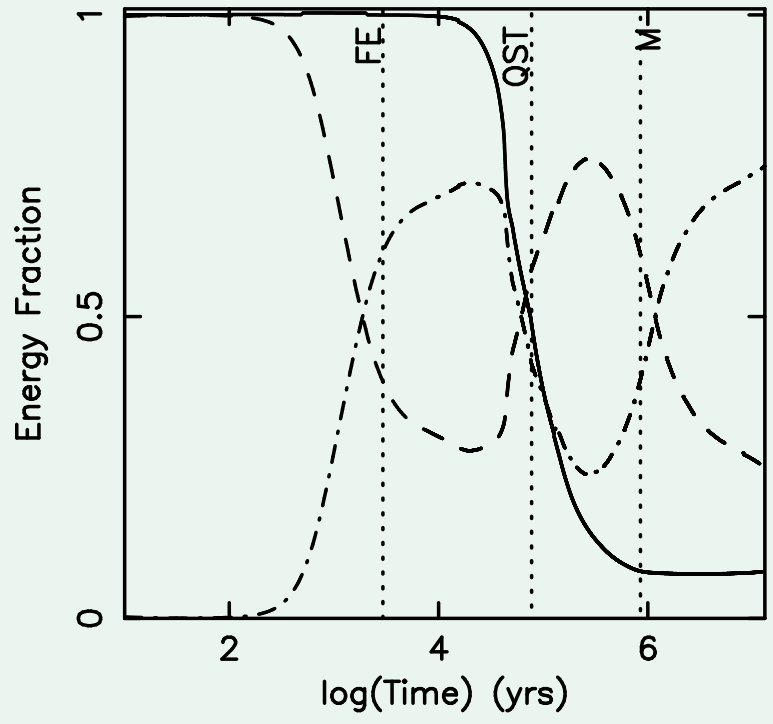
Supernova Remnants

- Parameters: n_0, M_{ej}, E_0
- Different evolutionary stages depending on
  1. Ratio of swept-up mass to ejecta mass
  2. Radiative cooling

Classical Theory

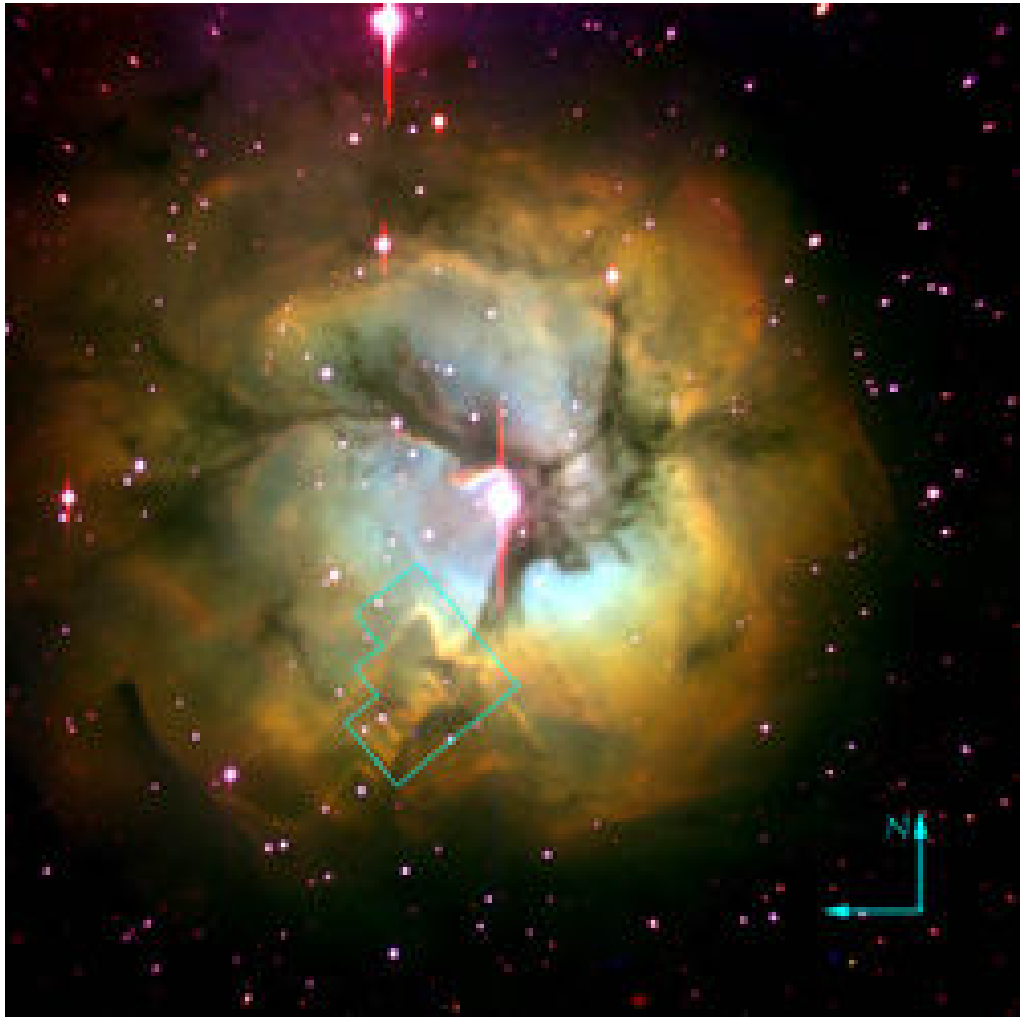
Supernova Remnants





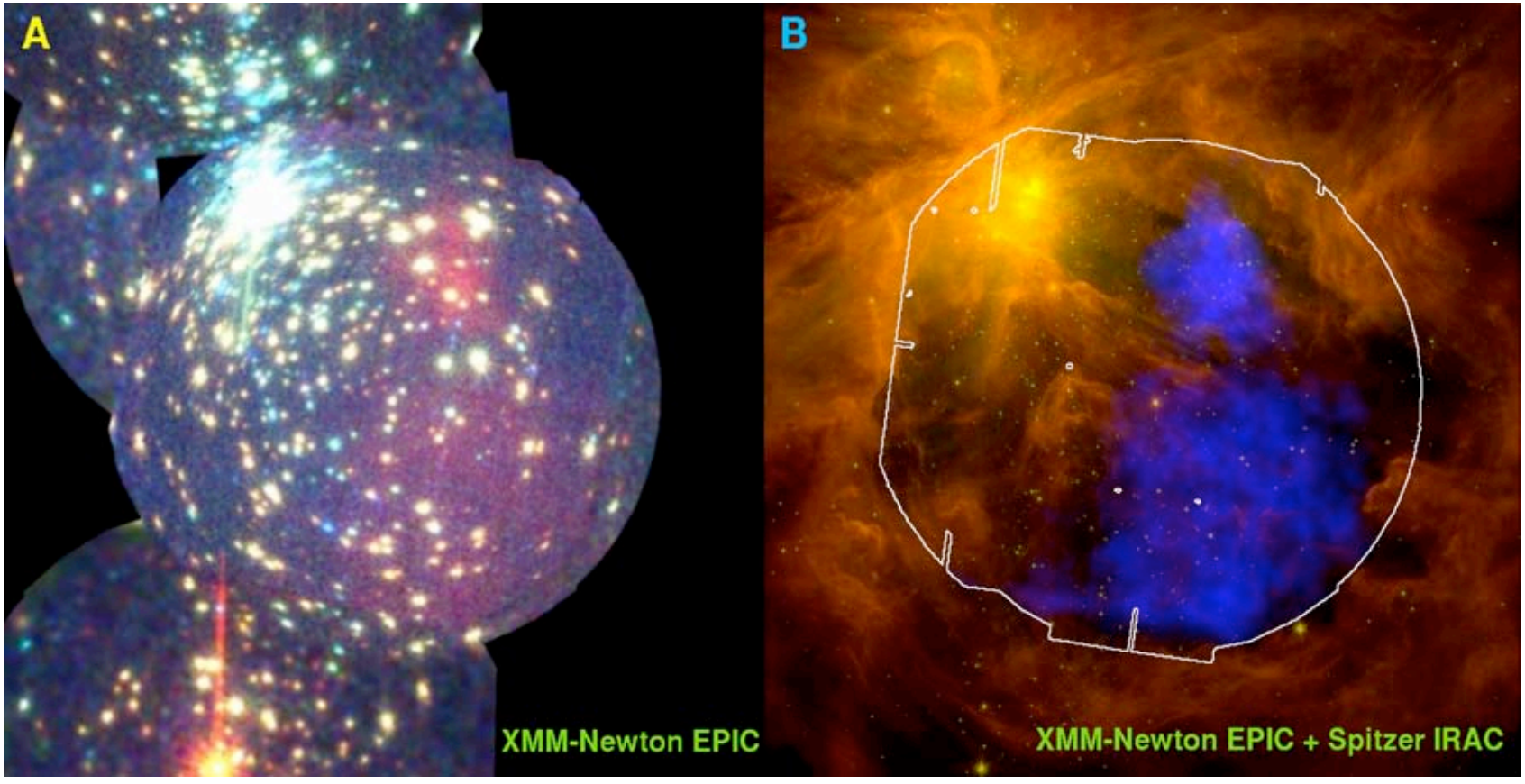
Refs: [Dyson, Arthur & Hartquist 2002]

Rogues' Gallery: HII Regions



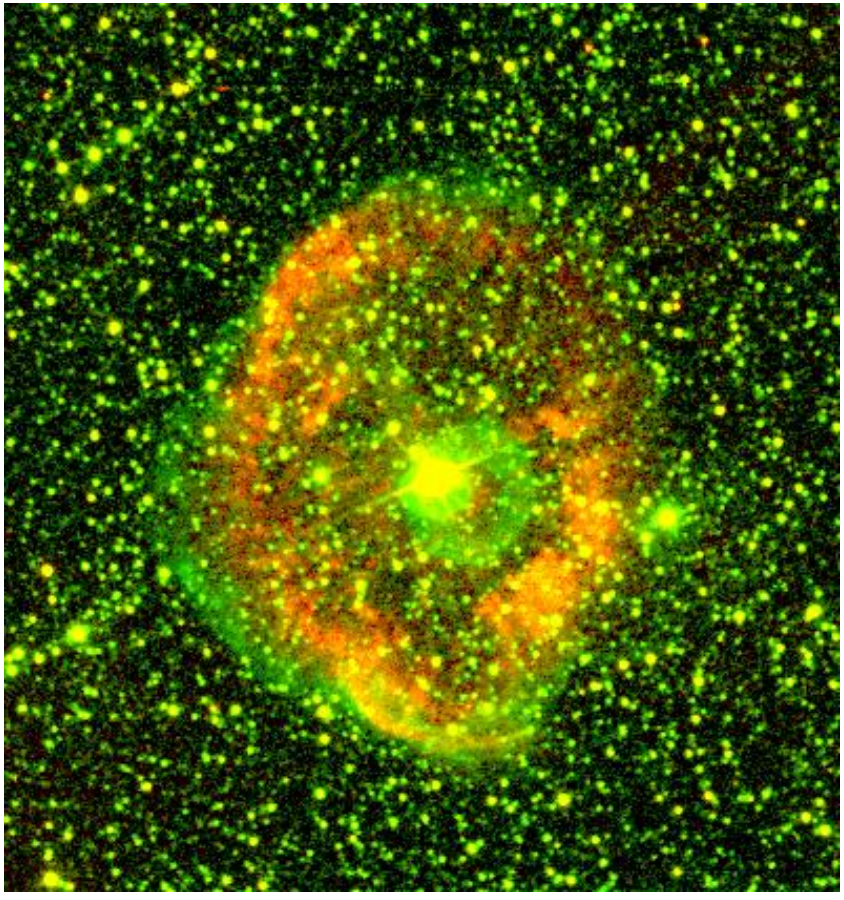
Refs: [Trifid nebula in [OIII] (blue), Hα (green) and [NII] (red): Hester (Palomar image)]

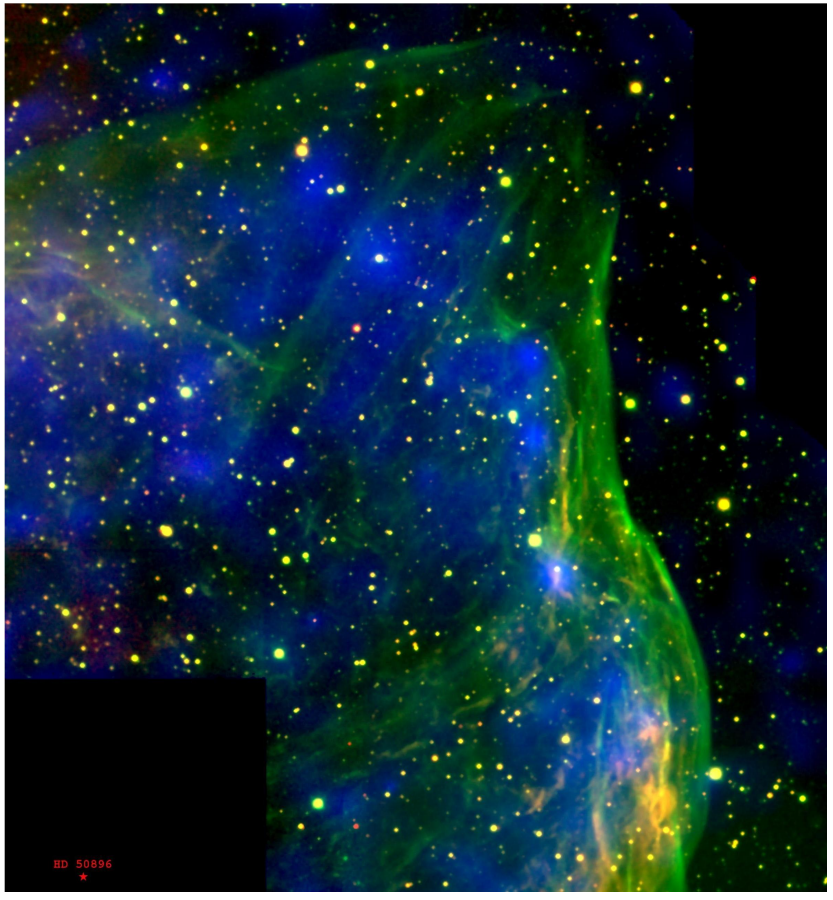
Rogues' Gallery: HII Region plus Stellar Wind



Refs: [Orion Nebula in diffuse, soft X-rays: Güdel et al. 2008]

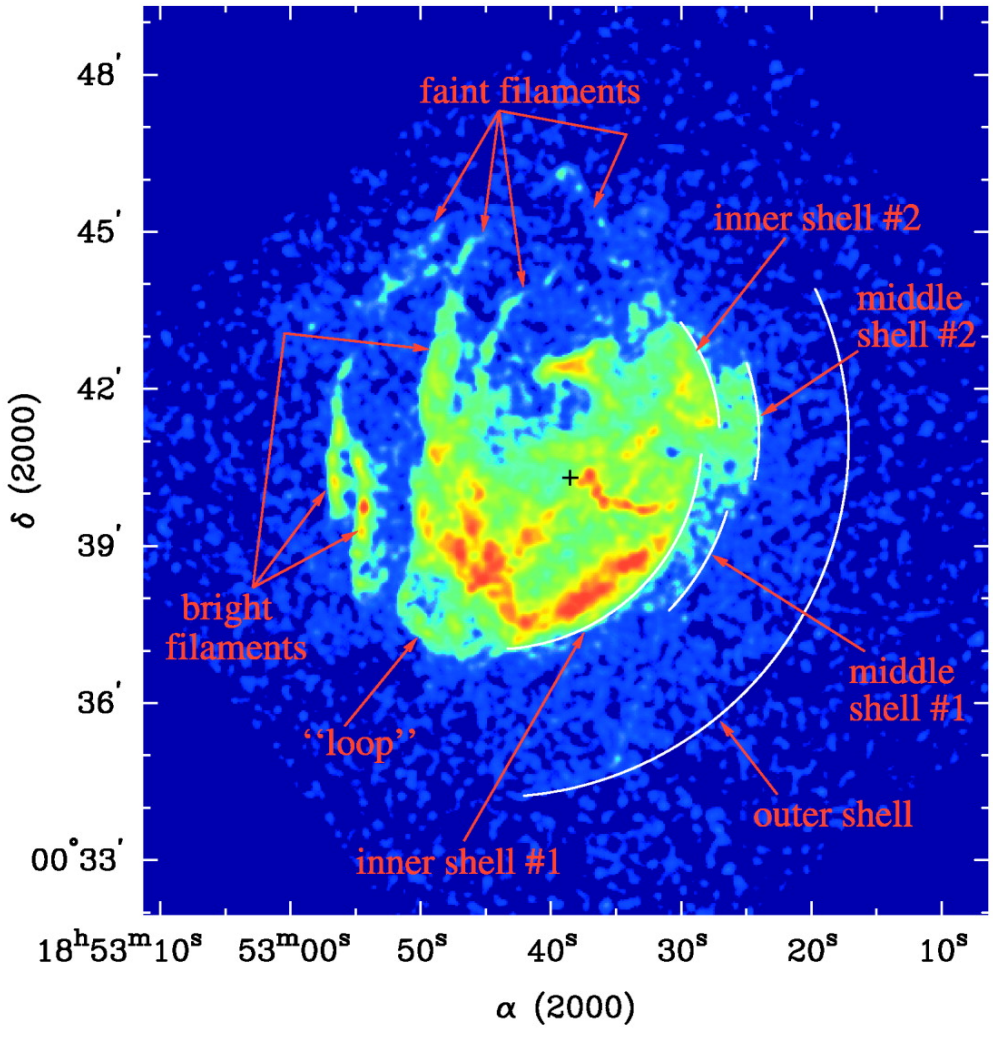
Rogues' Gallery: Wolf-Rayet Bubbles





Refs: [[OIII] and Hα image of RCW58: Gruendl (Gallery); [OIII] and XMM-Newton X-Ray image of S308: Chu et al. 2003]

Rogues' Gallery: Supernova Remnants



Refs: [Chandra image of Kesteven 79: Sun et al. 2004]

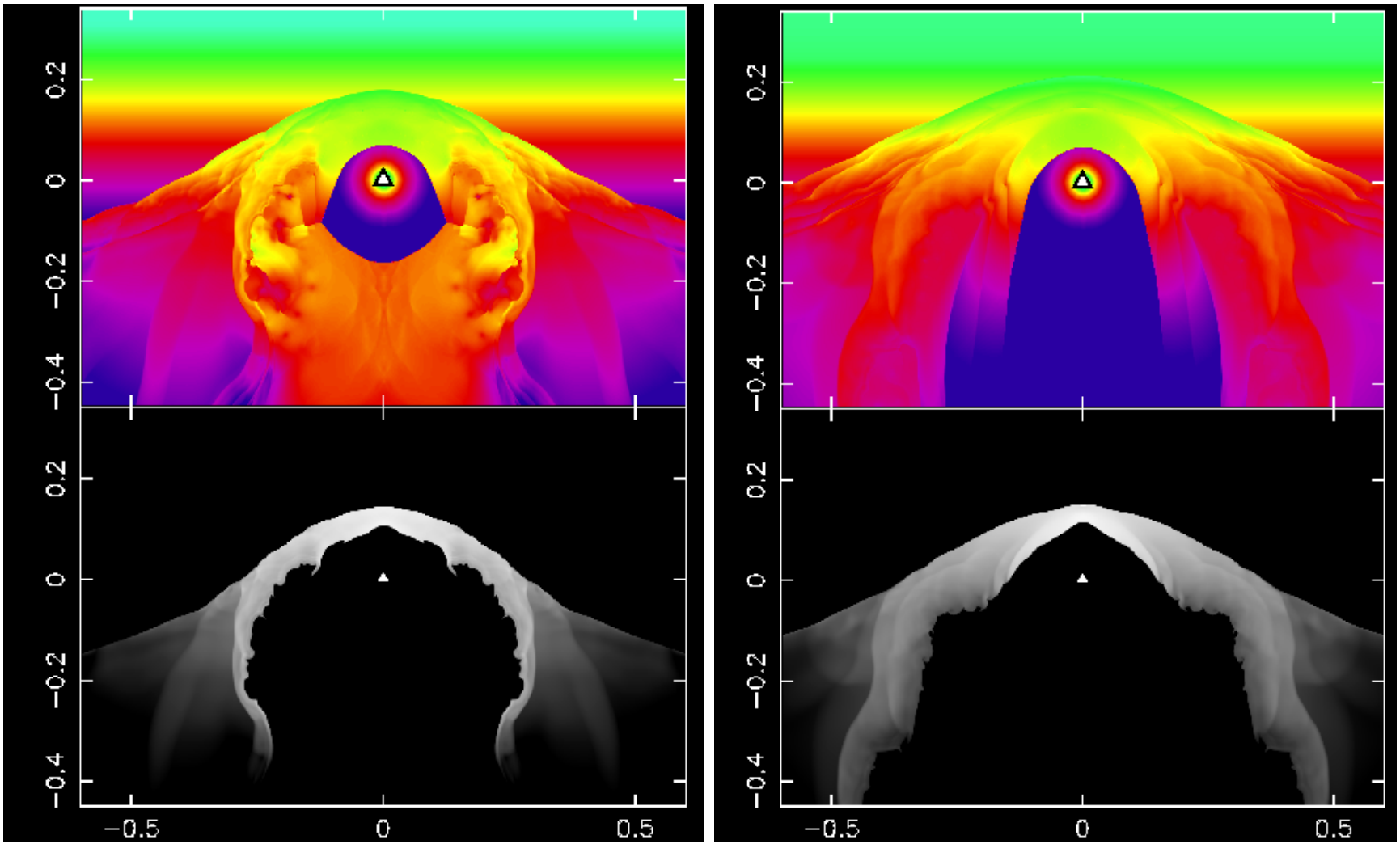
Modifications to Classical Models

- Non-uniform density
- Variations in the source
- Extra physical processes

Modifications: Density Gradients and Stellar Motion

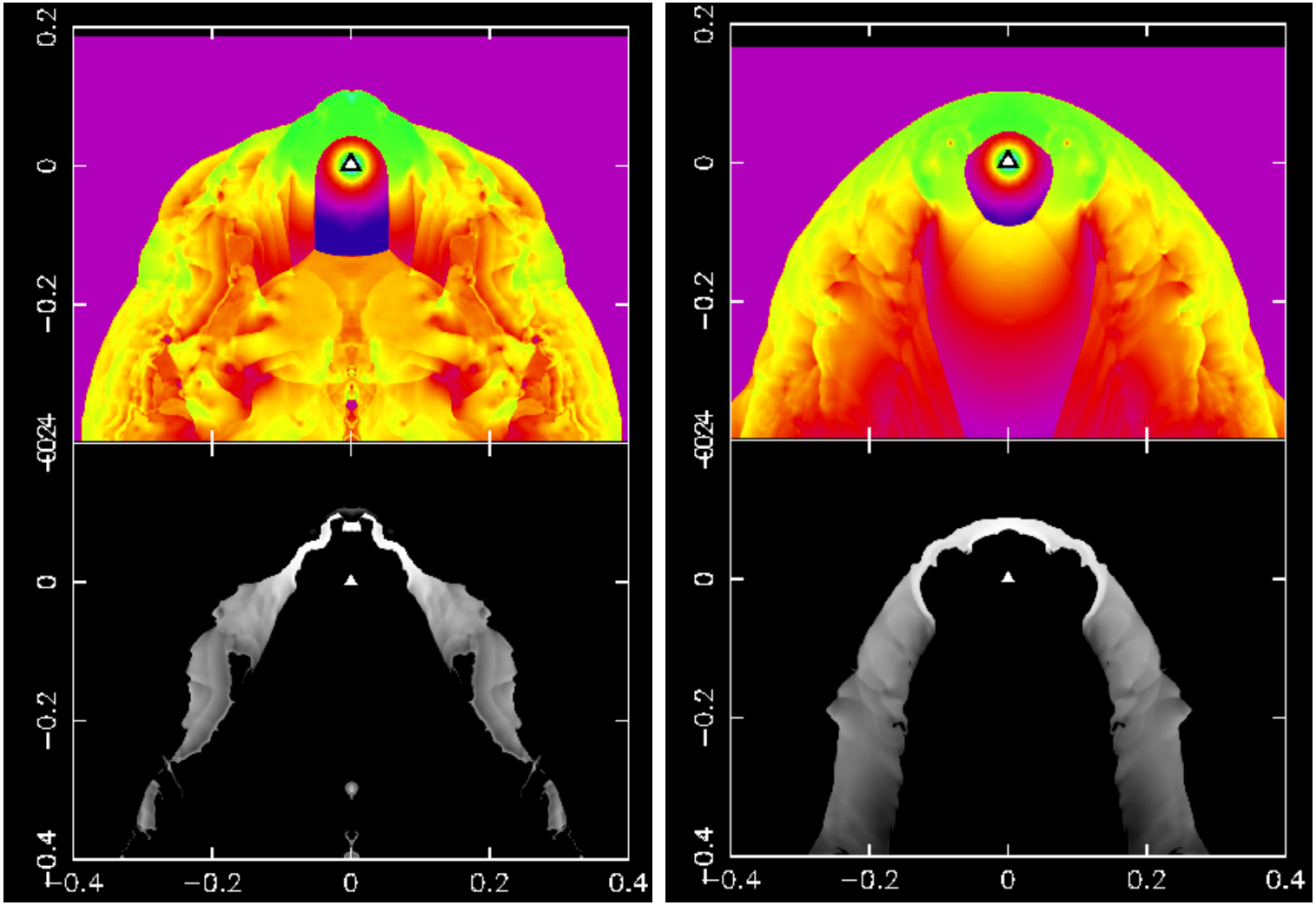
- Colour plot — pressure
- Greyscale — ionized density
- Left panel — after 20,000 yrs
- Right panel – after 40,000 yrs

Modifications: Density Gradients



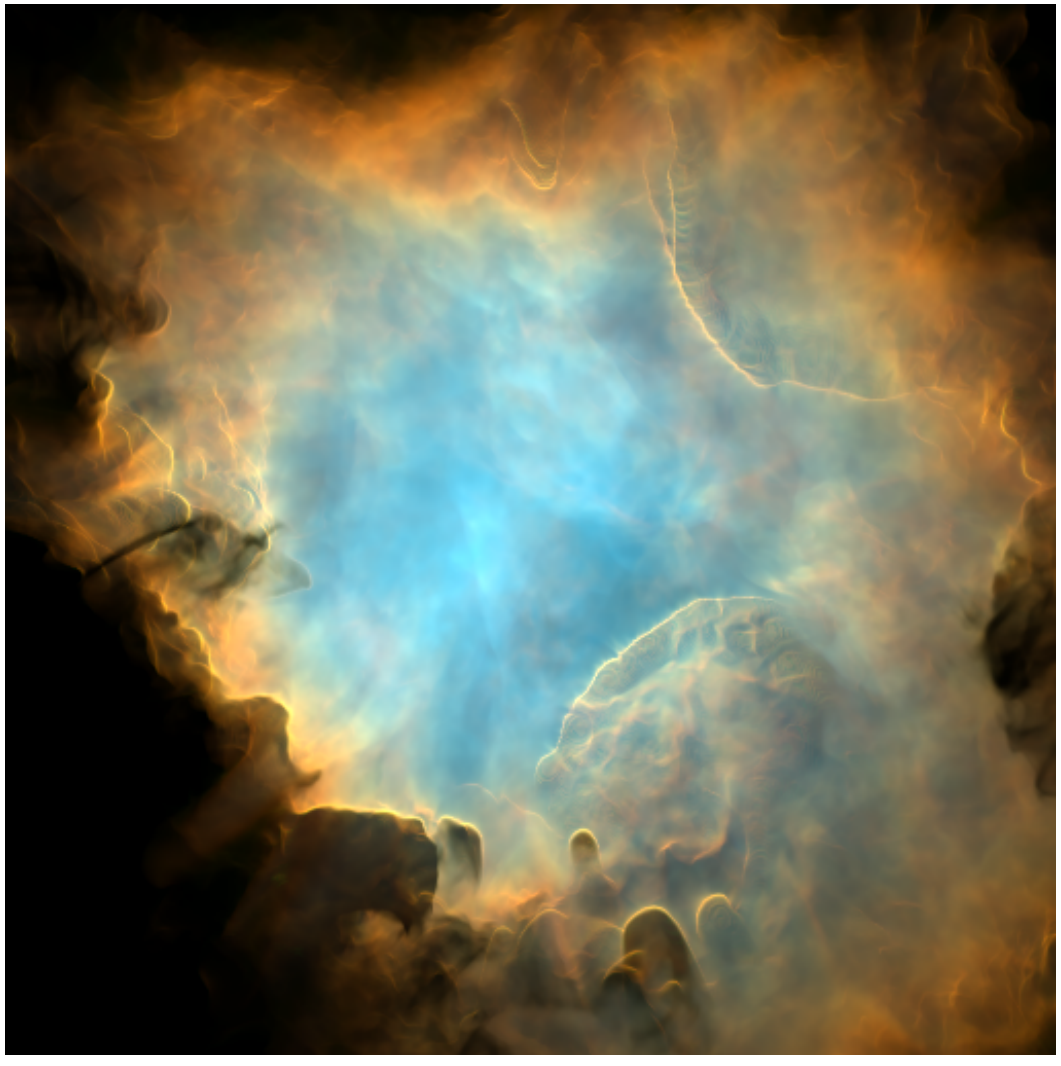
Refs: [Exponential density gradient: Arthur & Hoare 2006]

Modifications: Stellar Motion



Refs: [Star moving at 10 km s^{-1}: Arthur & Hoare 2006]

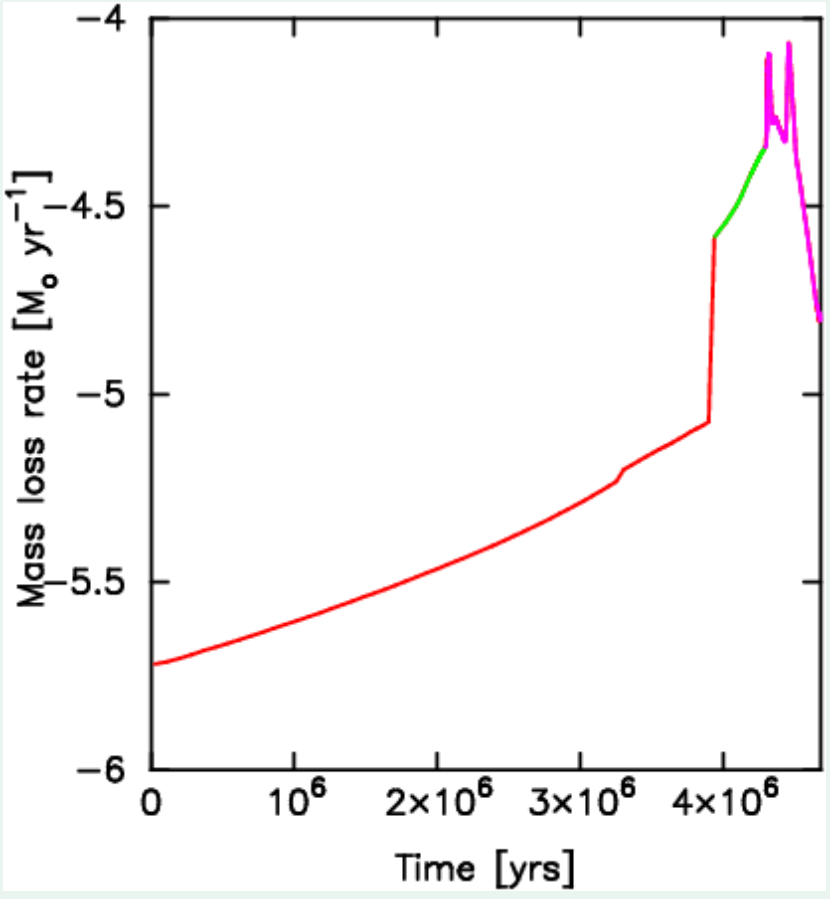
Modifications: HII Regions in Turbulent Media



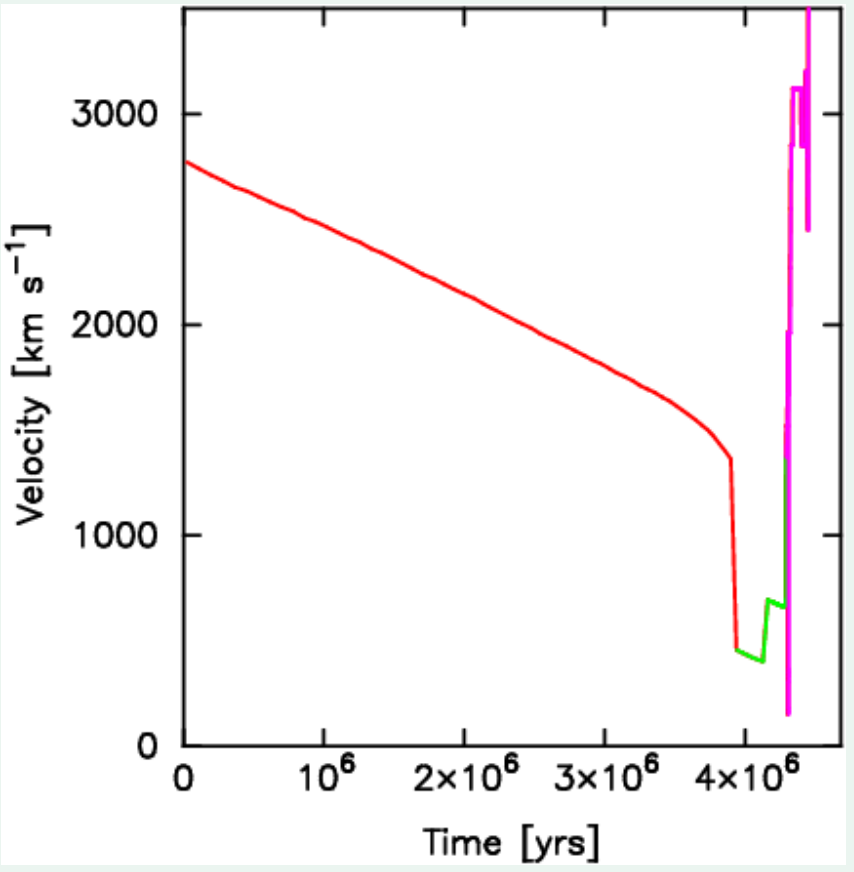
Refs: [Synthetic [OIII], Hα and [NII] emission-line image from a 512^3 numerical simulation: Mellema, Henney, Arthur & Vázquez-Semadeni 2009]

Modifications: Variations in the source

Mass loss rates



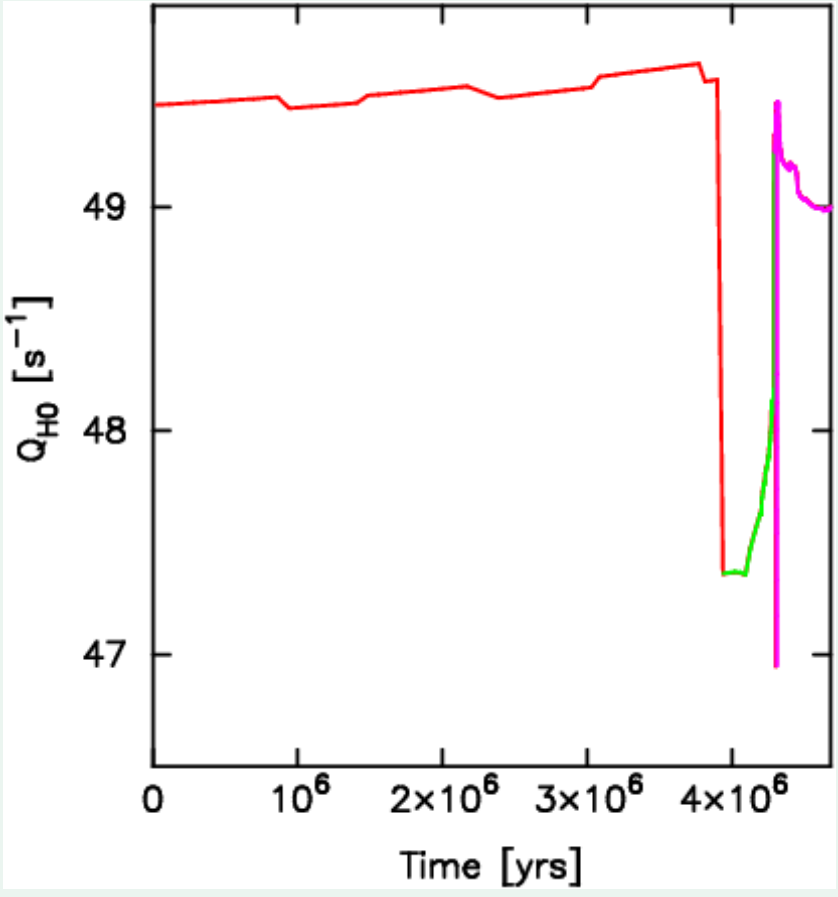
Stellar wind velocity



Refs: [Stellar evolution with rotation, $60M_{\odot}$: Meynet & Maeder 2003, 2005] [Kudritzki 1989]

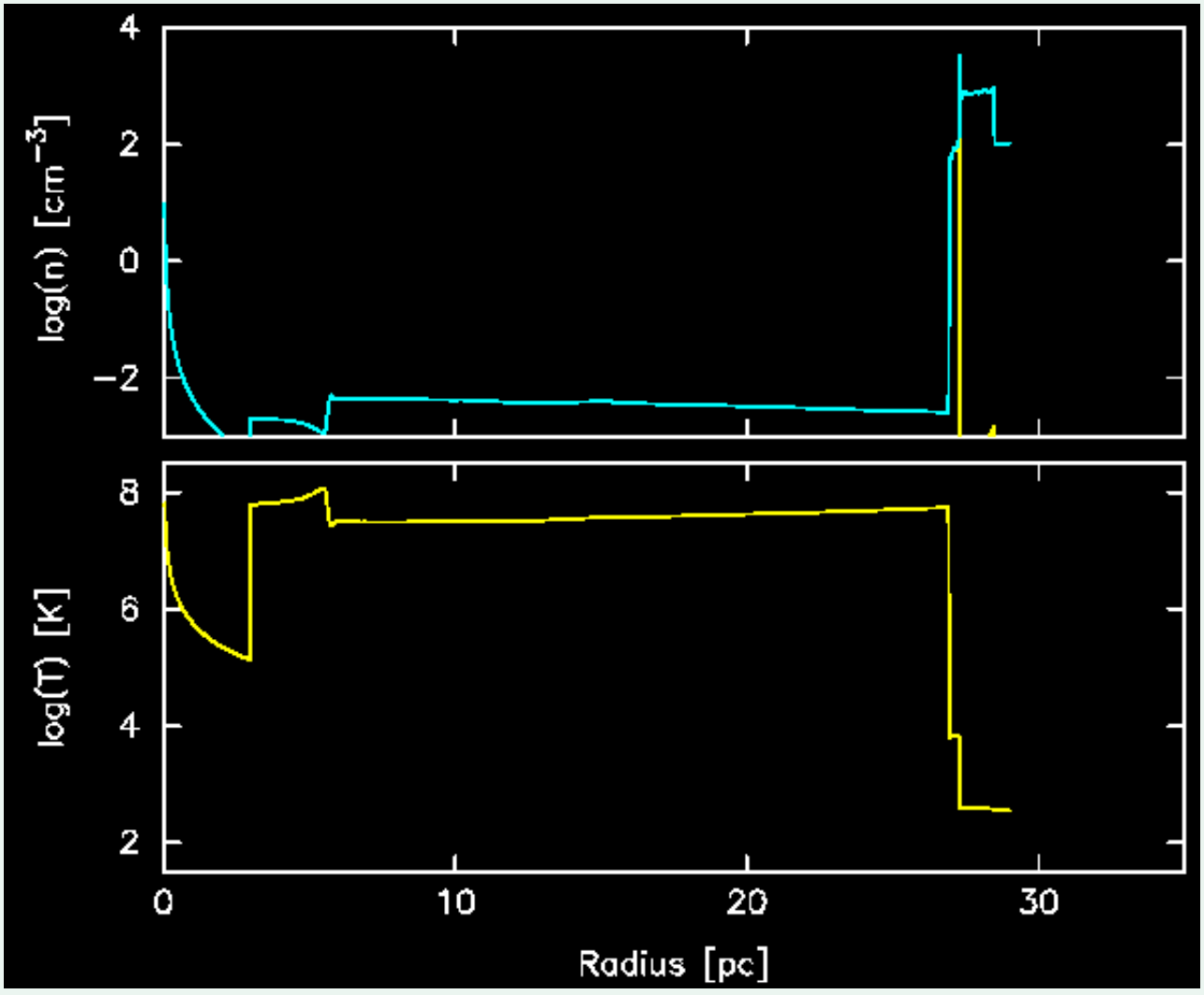
Modifications: Variations in the source

Ionizing photon rates



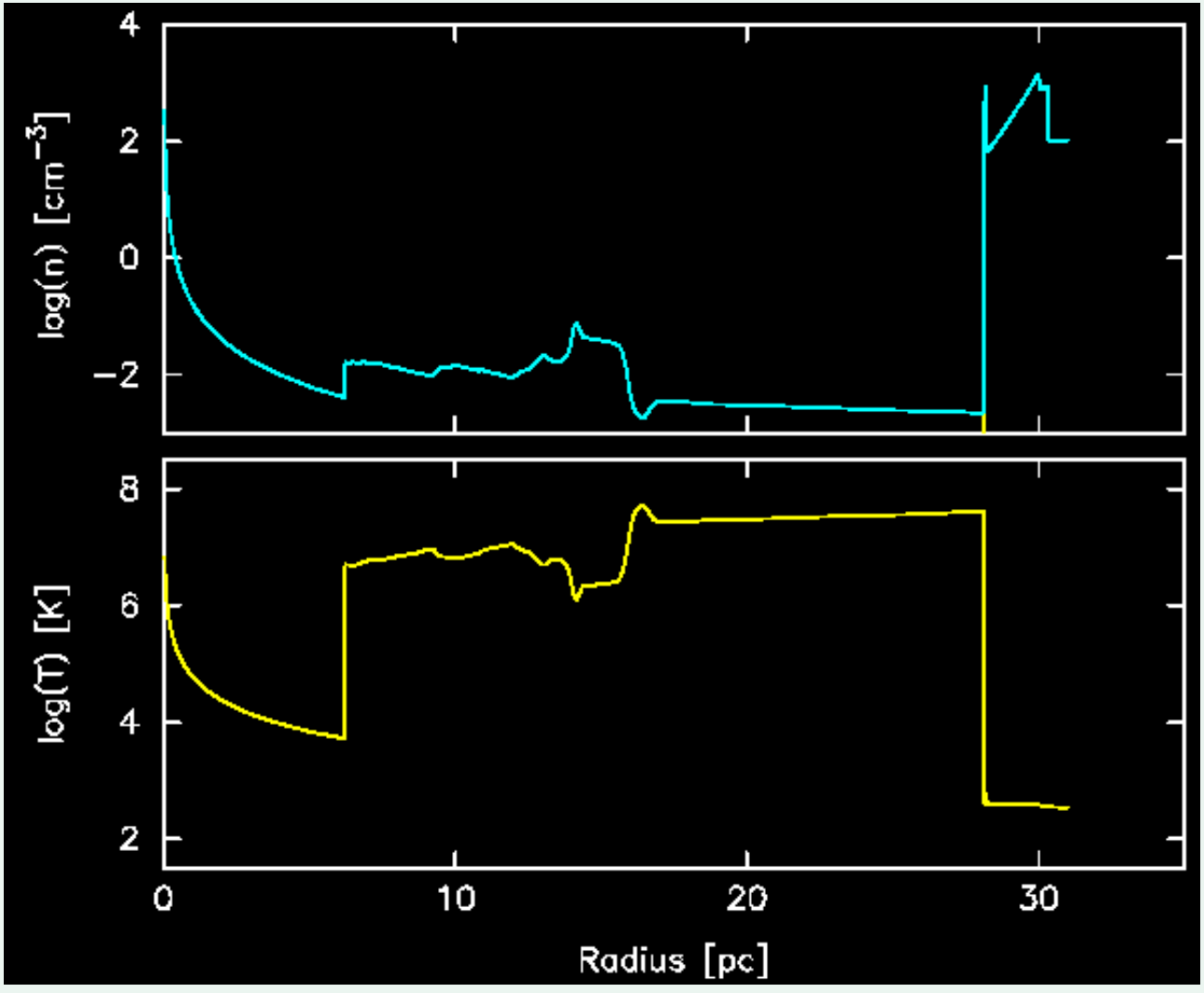
Refs: [Smith et al 2002; Starburst 99: Leitherer et al.]

Modifications: Variations in the source



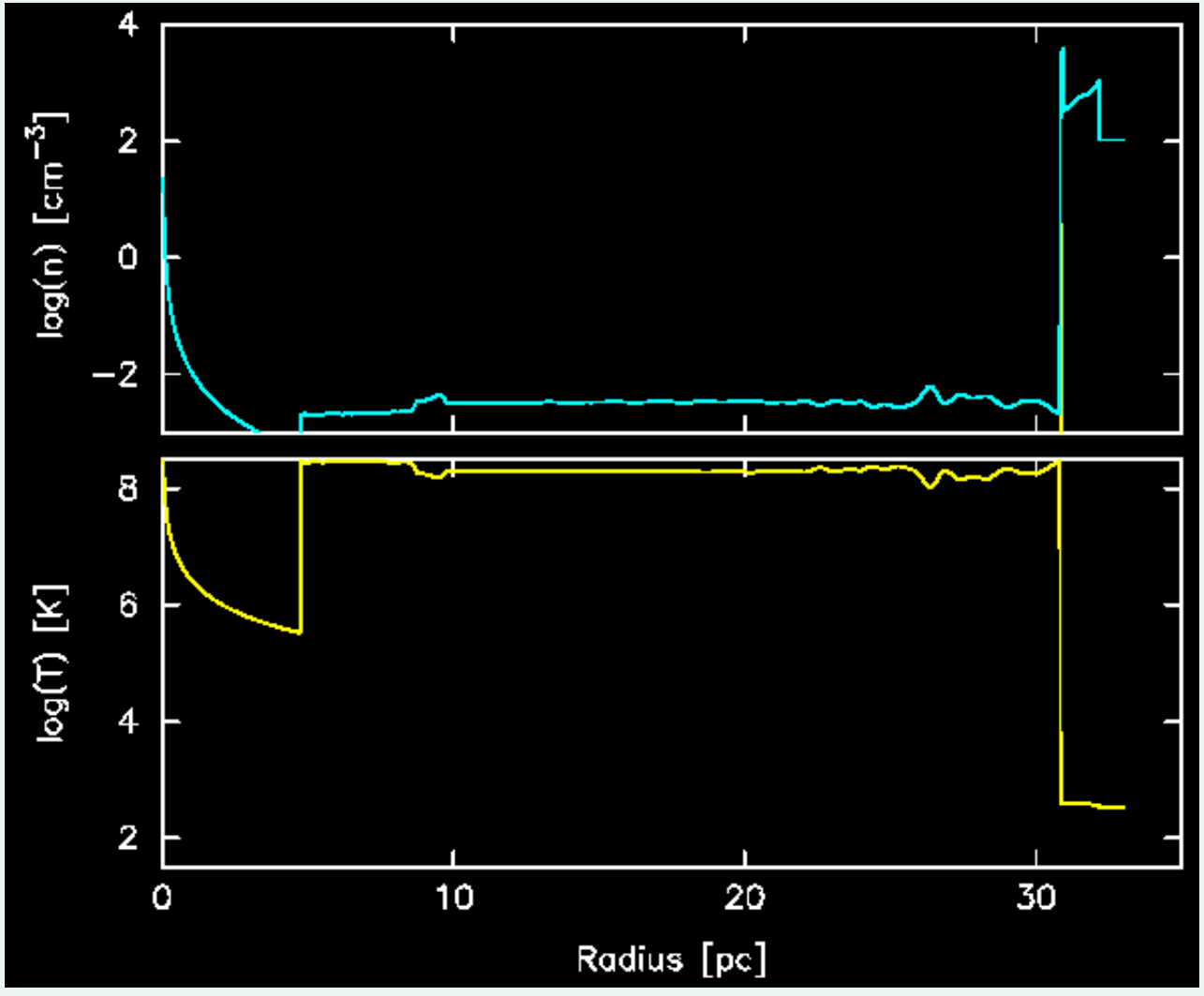
Key: [60$M_{\odot}$ model, Main Sequence Stage] [Top: (cyan) neutral density, (yellow) ionized density] [Bottom: temperature]

Modifications: Variations in the source



Key: [60$M_{\odot}$ model, LBV Stage] [Top: density] [Bottom: temperature]

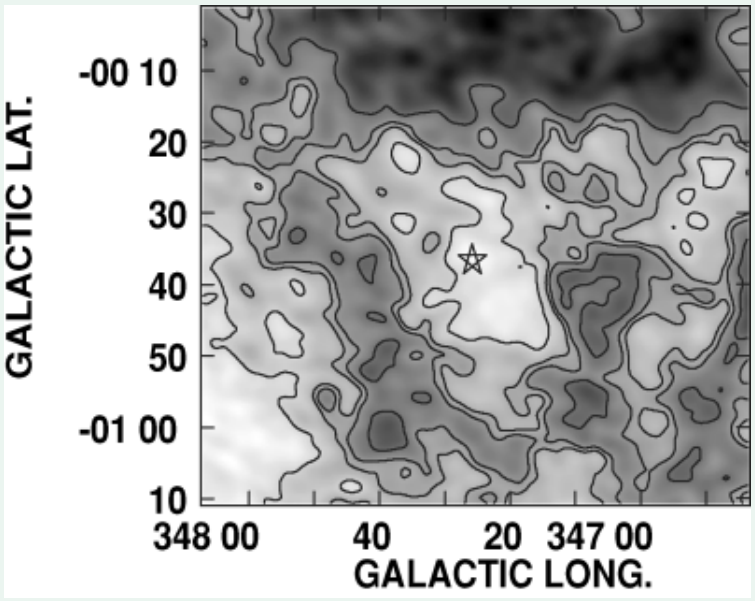
Modifications: Variations in the source

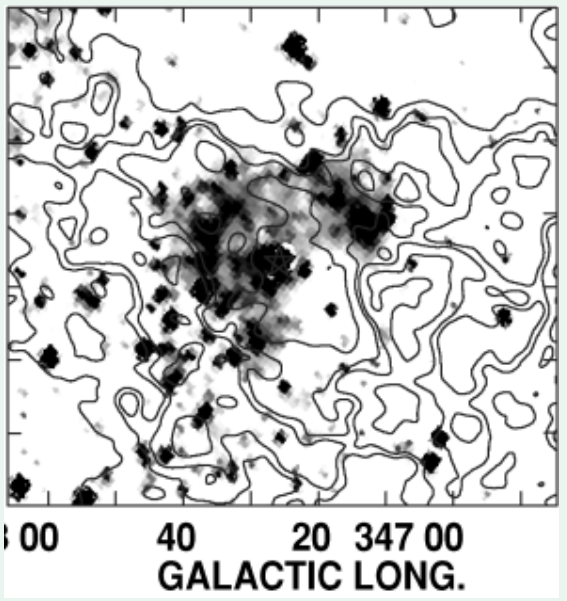


Key: [60$M_{\odot}$ model, Wolf-Rayet Stage] [Top: density] [Bottom: temperature]

Source variations

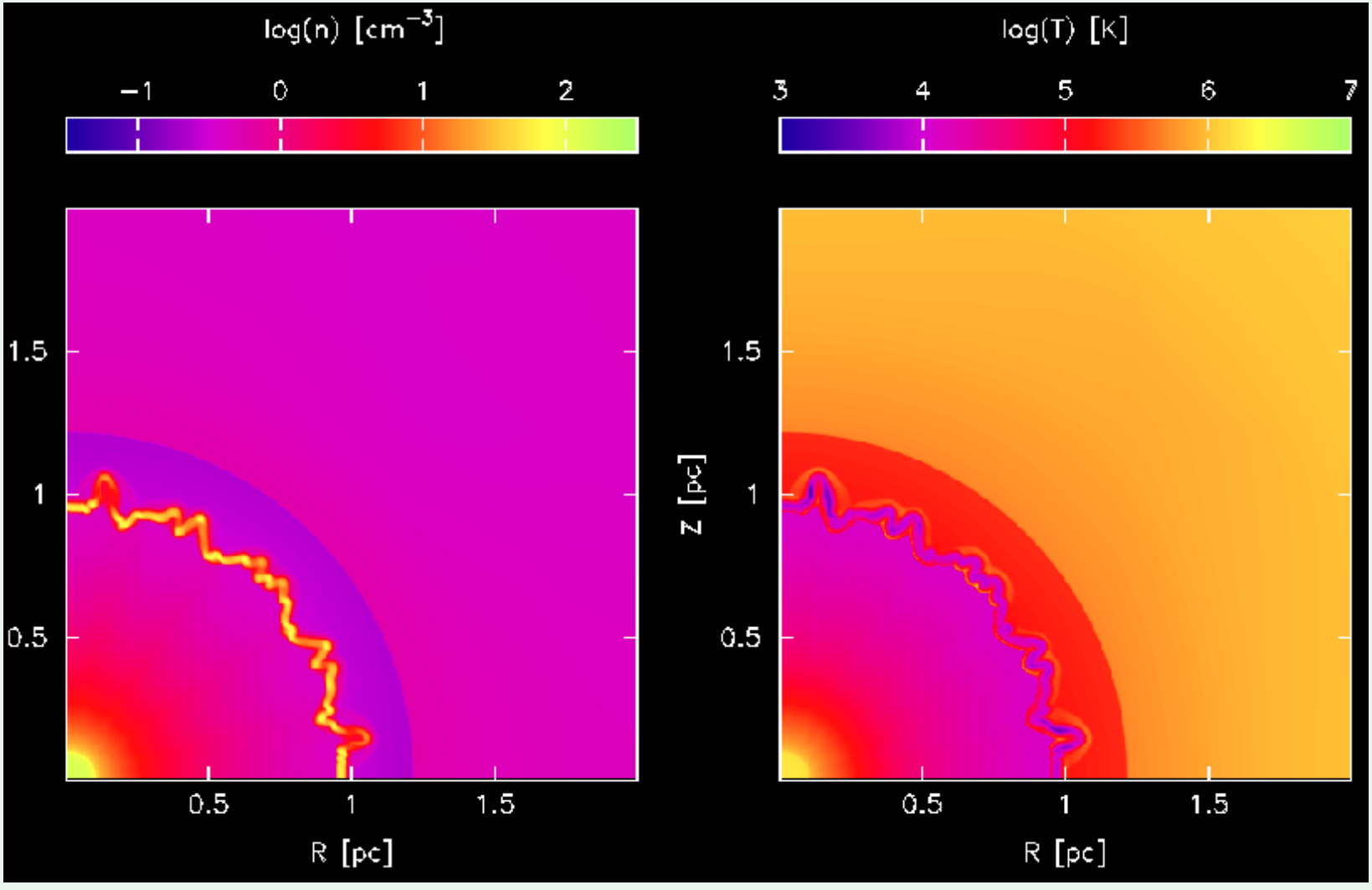
HI Shells





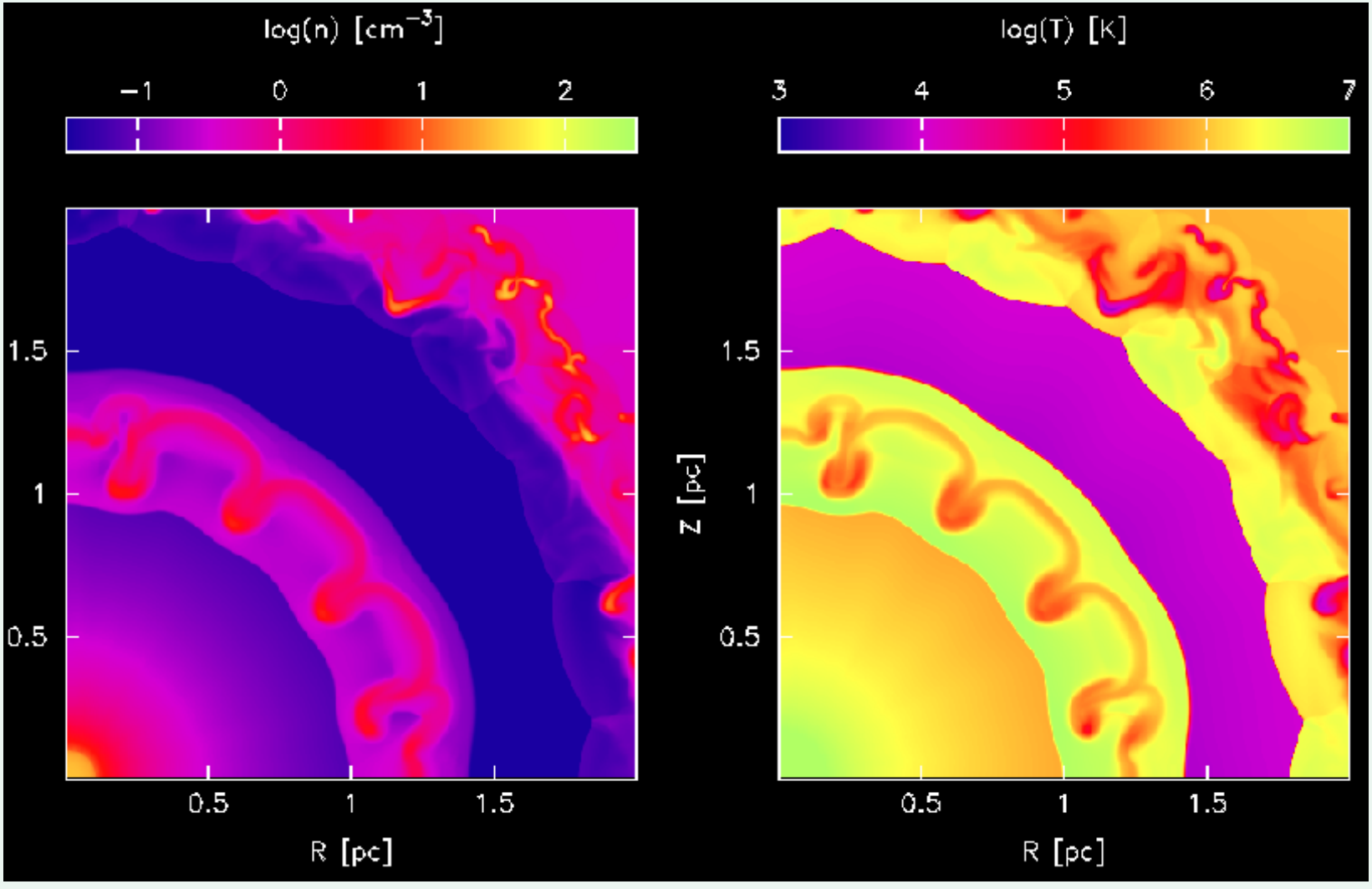
Refs: [RCW 118: Vásquez et al. 2005]

Source variations: Generate instabilities in CSM



Key: [40$M_\odot$ star model: 5.624 × 10^6 yrs] [Left panel: Density] [Right panel: temperature]

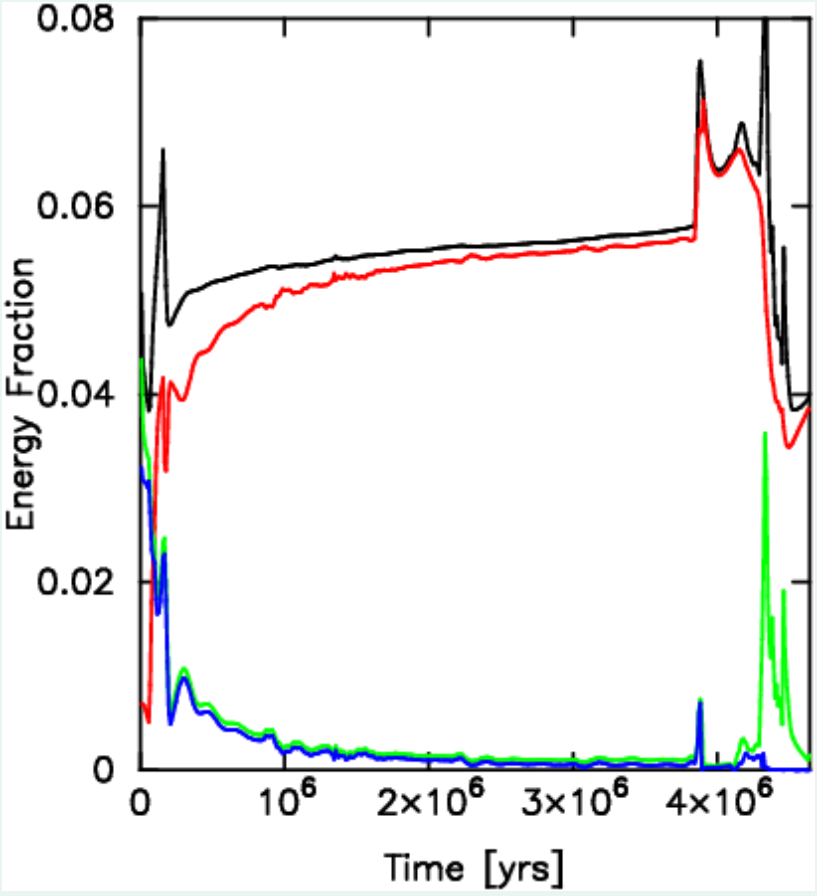
Source variations: Generate instabilities in CSM



Key: [40$M_\odot$ star model: 5.634 × 10^6 yrs] [Left panel: Density] [Right panel: temperature]

Source variations

Gas kinetic energy

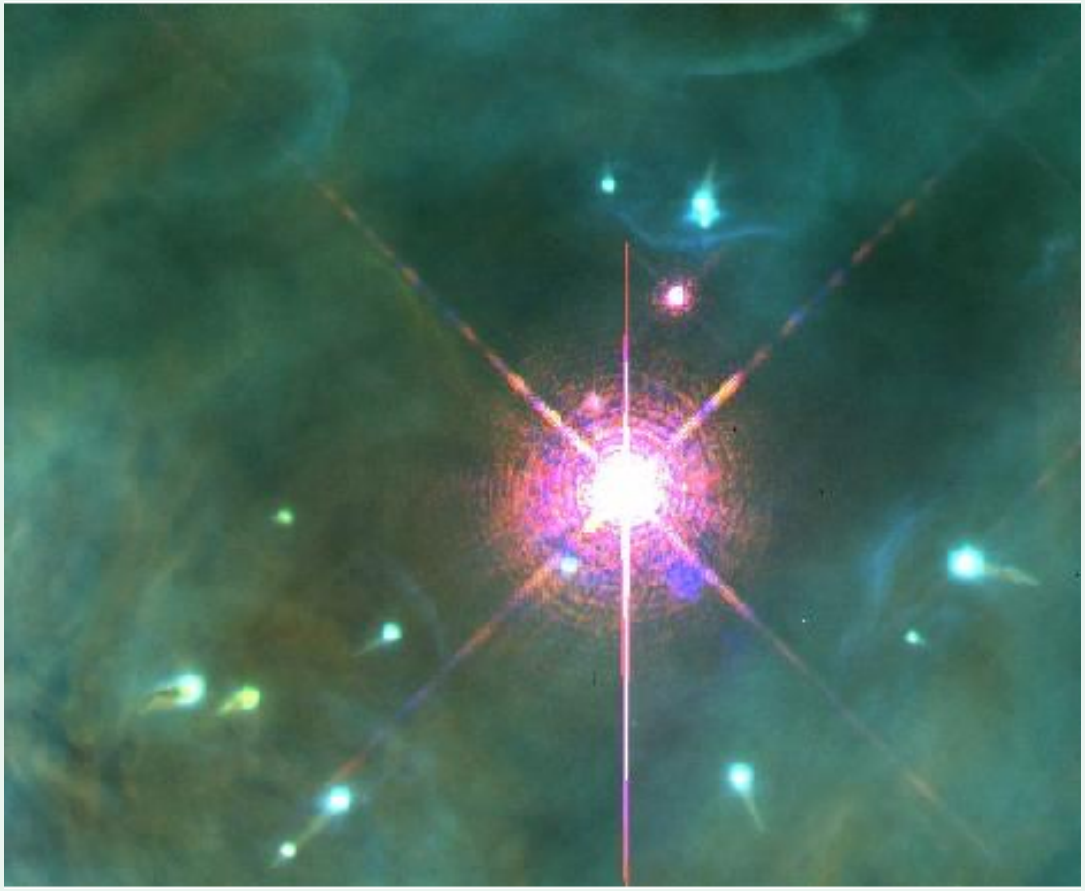


Modifications: Extra processes

- Thermal conduction
- Mass loading
- Magnetic fields

Modifications: Extra processes – Mass Loading

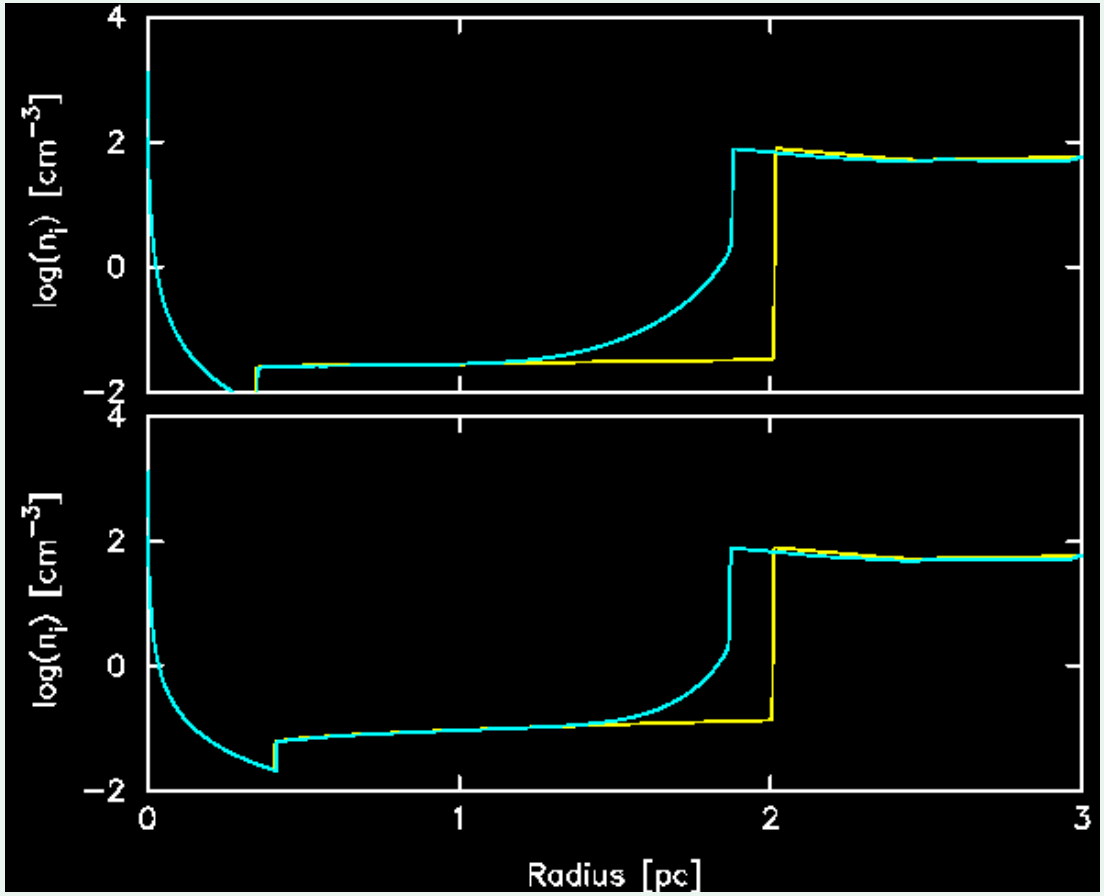
Mass loading...



Refs: [Bowshocks form at the interaction zone between photoevaporated material from the proplyds and the fast stellar wind from the main ionizing star of the Orion Nebula: O'Dell et al.]

Modifications: Conduction and Mass Loading

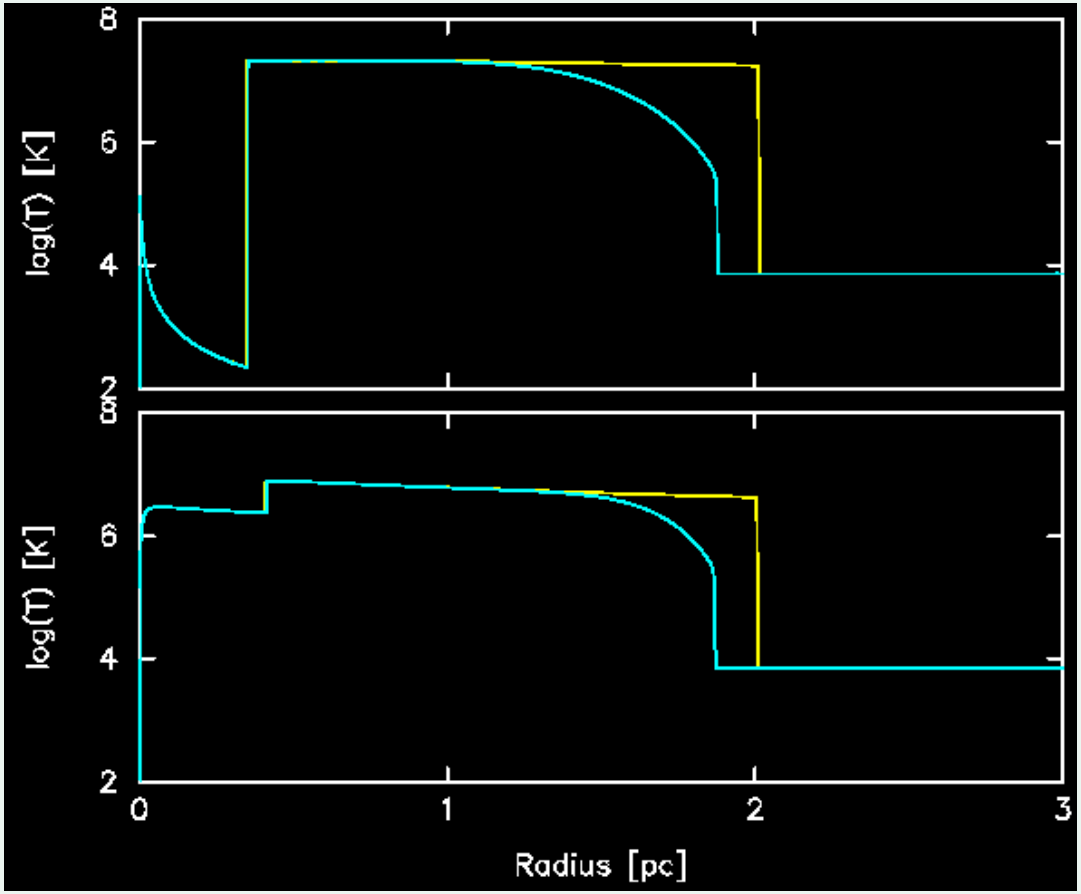
Density



Key: [Top panel: Without mass loading] [Bottom panel: With mass loading] [Yellow: Without thermal conduction; Cyan: With thermal conduction]

Modifications: Conduction and Mass Loading

Temperature

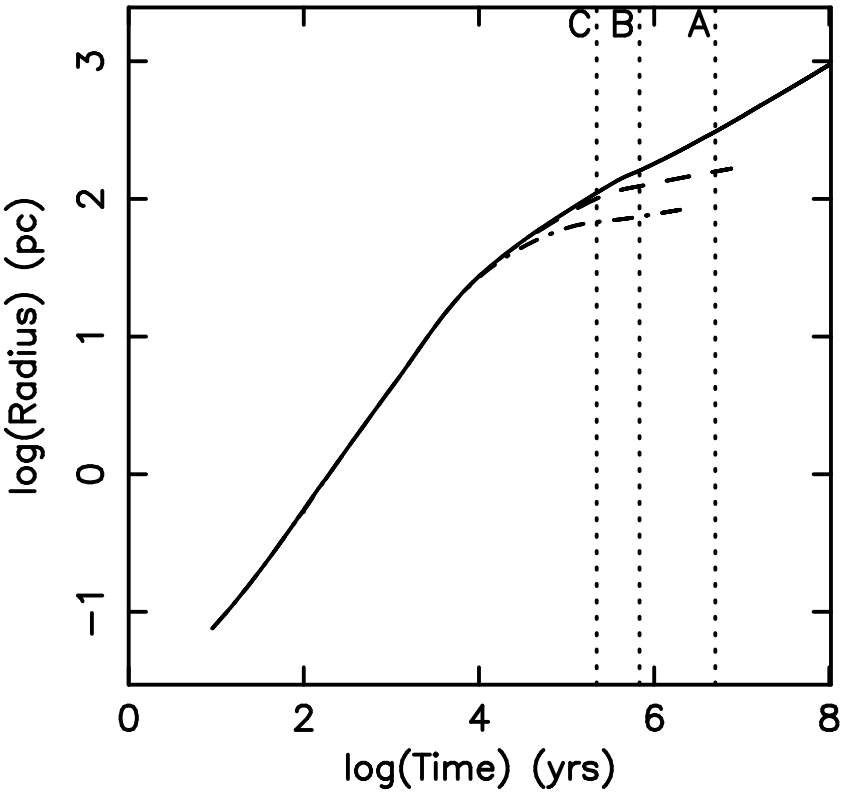


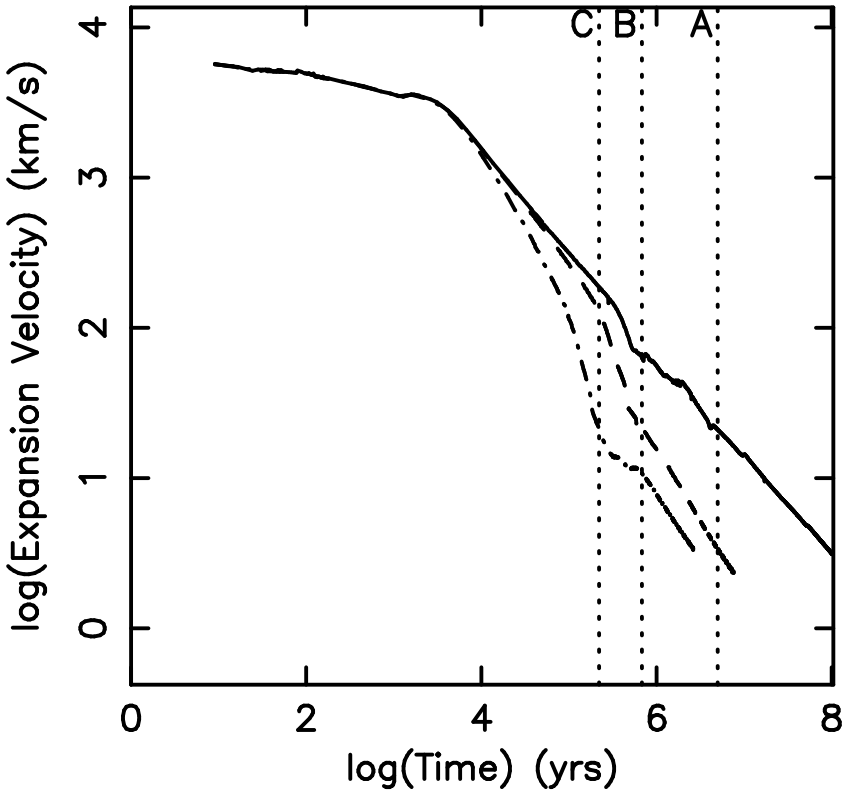
Key: [Top panel: Without mass loading] [Bottom panel: With mass loading] [Yellow: Without thermal conduction; Cyan: With thermal conduction]

Modifications: conduction

Thermal conduction has been suggested as an explanation for uniform temperatures across mixed morphology supernova remnants.

Modifications: Extra processes, mass loading



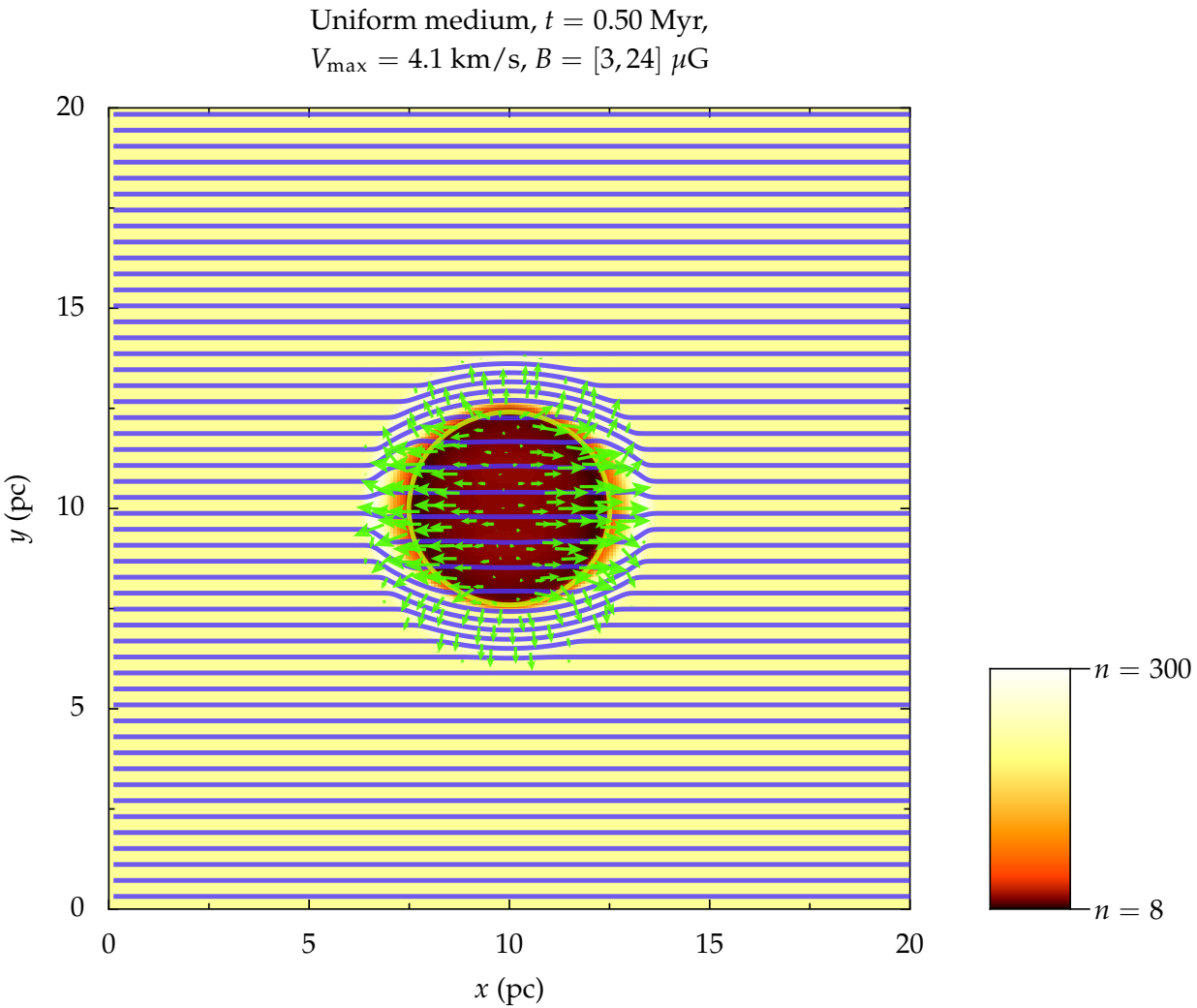


Refs: [Dyson et al. 2002]

Modifications: Magnetic fields

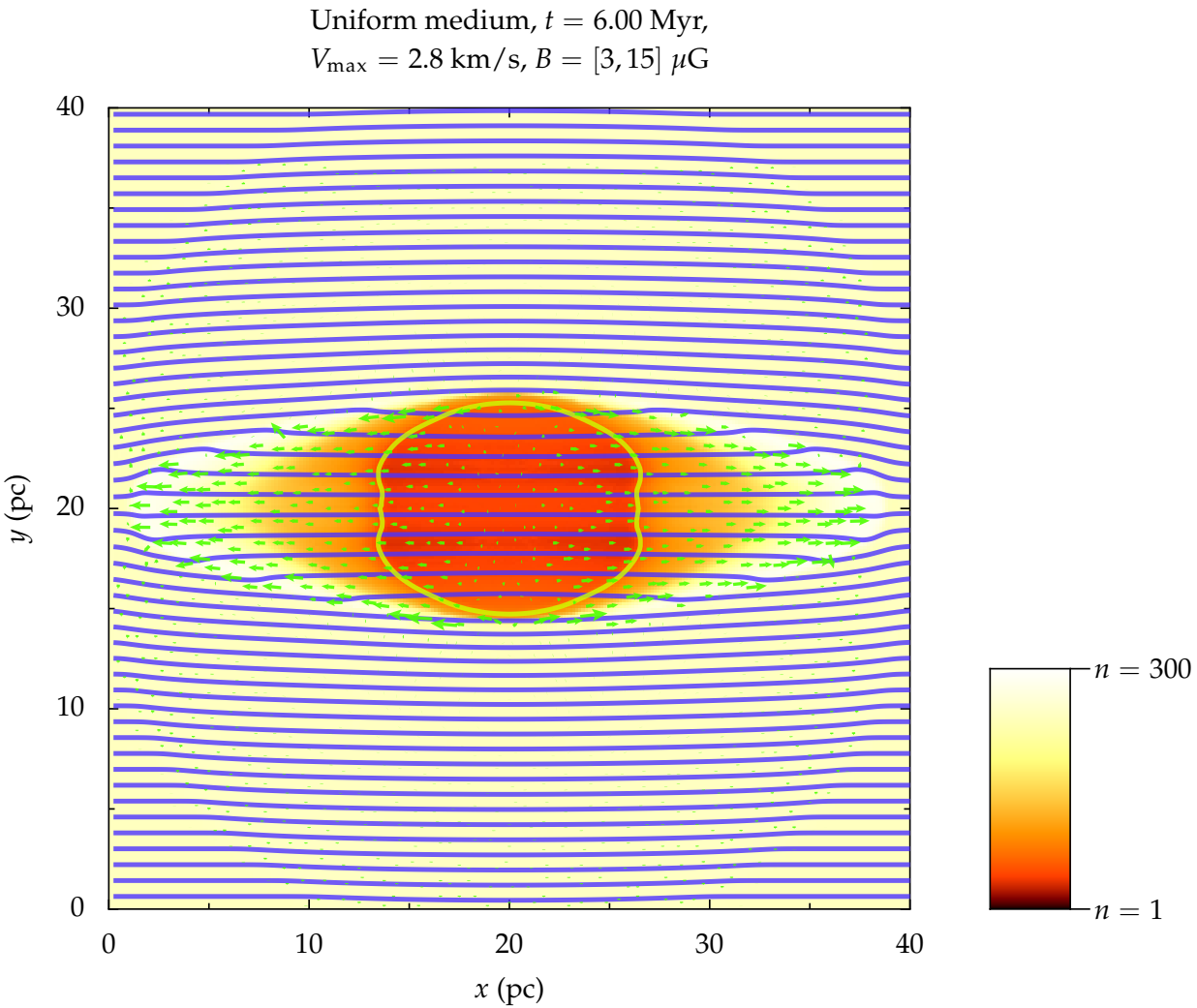
- Inhibit thermal conduction
- Weakly magnetized wind $\rightarrow$ aspherical bubble
- Affect SNR expansion at late times.

Uniform Density MHD HII Regions



Refs: [Henney, Arthur, de Colle, Mellema 2008]

Uniform Density MHD HII Regions



Refs: [Henney, Arthur, de Colle, Mellema 2008]

Summary

- Radiation-hydrodynamic modeling shows how different structures form and evolve around massive stars.
- Bubble size and amount of energy imparted to interstellar medium depend on processes taken into account.
- X-ray observations show that simple analytical models are inadequate to explain the observed emission.
- What is the magnetic field configuration and what role does it play?